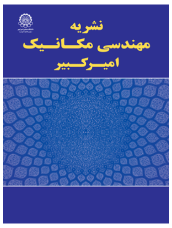

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Three Dimensional Design and Finite Element Analysis of Scaffold for Use in Damaged Bone Tissue

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ABSTRACT: Major bone defects, especially in long bones such as the femur, which can result from trauma, tumor, or bone infection, are among the most common injuries a person faces daily. This research presents a practical and accurate process for designing bone tissue engineering scaffolds to treat bone injuries. For this purpose, computed tomography-Scan images of the area related to the human femur were obtained. A bone defect caused by bone damage was made in the cortical and trabecular parts. Next, the outer surface of the damaged parts was designed with an ideal geometry. The design of the unit building cell of the internal structure of the scaffold was also done with simple cubic geometry. Finite element analysis was used to investigate the effect of porosity on the Young modulus of the unit cell. Finally, using the results of finite element analysis, a unit cell with an edge size of 0.972 mm and pore size of 0.6 mm was designed to reconstruct the cortical part, and a unit cell with an edge size of 0.972 mm and a strut thickness of 0.165 mm was designed to rebuild the trabecular part. The scaffold designed in this study has a geometry that matches the geometry of the damaged part in its ideal state and provides the necessary conditions for cell proliferation and diffusion of nutrients.

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1- Introduction

Injury, disease, and birth defects have always been part of the human experience. Basic bone defects, especially in long bones such as the femur, which can be the result of trauma, tumor, or bone infection, are among the most common injuries that humans face in daily life. As with any successful and practical action, challenges have arisen in this field over time. Artificial structures need better compatibility and biological performance. Organ transplantation also has problems such as anatomical limitations and tissue rejection by the body's immune system in some cases. These problems and limitations caused to turn to new treatment methods [1]. Tissue engineering as a new therapeutic method is a developing approach for the regeneration and repair of damaged tissues. In 1993, Langer and Vacanti introduced tissue engineering as a multidisciplinary field that uses the principles of engineering and biological sciences to develop biological alternatives to repair, maintain and improve the function of a tissue or organ [2]. Tissue engineering uses three basic tools cells, scaffolds, and growth factors to regenerate and repair damaged tissues. In the process of tissue engineering, cells are cultured on a scaffold and the scaffold provides a suitable environment for the growth, proliferation, and differentiation of cells. After being transferred to the scaffold, the function of growth factors is to help the cells to regenerate the damaged tissue [3]. As one of the main parts of tissue engineering, the scaffold must be able to simulate the functions of the natural extracellular matrix well. However, due to the multiple functions, complex composition, and dynamic nature of the extracellular matrix, its exact simulation is very difficult. Tissue engineering scaffolds must have porosity and pores of appropriate size and geometry to allow the growth and proliferation of cells and the transfer of nutrients and oxygen. On the other hand, the scaffold must have mechanical properties that match the mechanical properties of the tissue being regenerated [1, 3].

In this research, a practical process with optimal precision for the design of bone tissue engineering scaffolds has been presented. Computed Tomography (CT) scan images of the human femur area were used to create 3D models of the cortical and spongy parts of the femur. The external surface of the damaged parts was designed with an ideal geometry. The internal structure of the scaffolding was also done with simple cubic geometry.

2- Methodology

In the initial stage of this research, a CT scan of the human femur area was taken. As stated, bone defects are often caused by trauma, tumor, and infection. In the treatment process, the damaged part is removed from the bone and a scaffold is placed in its place. In this research, in order to ensure the

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correct design of the damaged part, an image was taken of a healthy and undamaged leg, and then the desired bone defect was created. Images were saved in DICOM format and imported into Mimics software. The images obtained from the CT scan are two-dimensional images in the form of sections with a certain distance in the directions of the three main anatomical planes. The entered images had a distance of 3 mm in the direction of the transverse plane, a distance of 0.68 mm in the direction of the frontal plane, and a distance of 0.68 mm in the direction of the middle plane. The imported images were used to make a three-dimensional model of the femur similar to the anatomical model. According to the studies [4] and CT scan images, the femur in the middle part has two main parts cortical bone and spongy bone. The desired parts were separated from the available images along the anatomical planes and 3D models were created from the cortical and spongy parts of the femur. A bone defect caused by bone damage was created in the obtained models, and finally, 3D-damaged models of the cortical and spongy parts of the femur were made. The comparison between the constructed 3D models and the anatomical model shows that the modeling is done well. Of course, it should be noted that gender, age, height, weight, diet, and mobility are factors affecting the biological and mechanical properties of the femur.

After creating 3D damaged models of the cortical and cancellous parts of the femur, these 3D models were transferred to CATIA software in STL format to design the external surfaces of the damaged parts with ideal geometry. The designed outer surface of each part actually makes the outer surface of the corresponding scaffold, and the single cell that forms the structure of the scaffold fills the inner space of this surface. Various methods can be used to design these surfaces. In one method, if the CT-Scan images of the opposite leg are also prepared, the 3D model of the opposite femur, which is projected to the middle plane, can be used to design the external surfaces of the affected parts. In another method, which is also used in this research, the lower and upper edges of the surfaces of the damaged femur models can be used to design the external surfaces. The files transferred to the CATIA software are in the form of networks of the bone surface that must be converted to the bone surface. The required corrections were made on these meshes and meshes with suitable quality were created from the damaged bone models. Then the surfaces of the damaged models were made using these networks. Finally, the surfaces of the damaged parts were designed with optimal accuracy. By assembling these designed surfaces in the damaged models and comparing them with real surfaces, it can be seen that the design has been done with acceptable accuracy.

3- Results and Discussion

Finite element analysis was used to evaluate the mechanical performance of the unit cell and as a result to calculate Young's modulus. For this purpose, the porous structures created by the unit cell in different porosities were saved in STEP format and transferred to ABAQUS software.

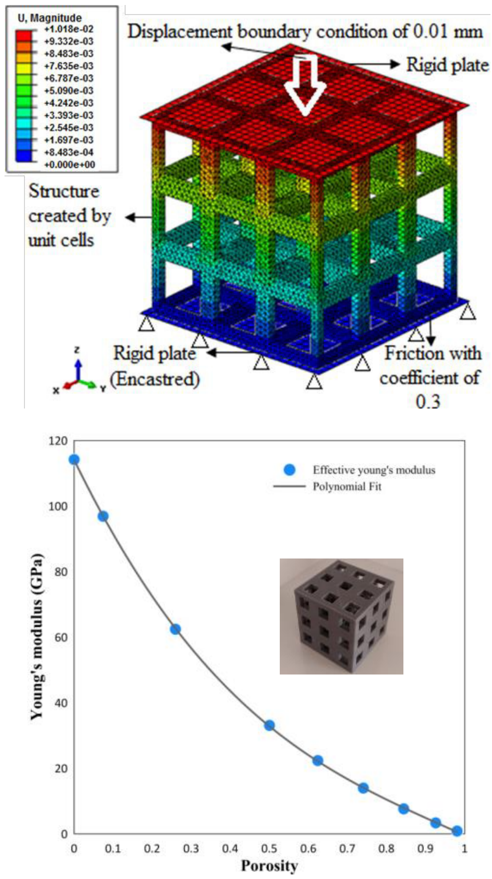

Fig. 1. Finite element model with boundary conditions and loading, and Diagram of Young's modulus changes in terms of porosity changes

Then these structures were subjected to compressive loading (Fig. 1). According to the studies [5-8], the validity of this method has been confirmed for the analysis of porous structures.

In the final step to design the scaffold, the unit cells designed for the cortical and spongy parts of the bone were used to fill the inner space of the designed external surfaces corresponding to each of the bone parts. By repeating each of these two single cells in three dimensions and creating an intersection between the created porous structure and the external surface designed for each of the bone parts, the scaffold structure was created for each of the parts (Fig. 2). Then, the two parts of the scaffolding are completely connected to each other and transformed in a unified manner (Boolean Operations). The external surfaces in both parts of the scaffold have high complexity, which makes the single cell adjacent to the external surface of the spongy part and the internal and external surfaces of the cortical part be cut at different angles and have an incomplete body. Due to the proper design of the unit cells, after assembling the two parts of the scaffold and despite the defects created in the border unit cells, a proper connection has been formed in the middle

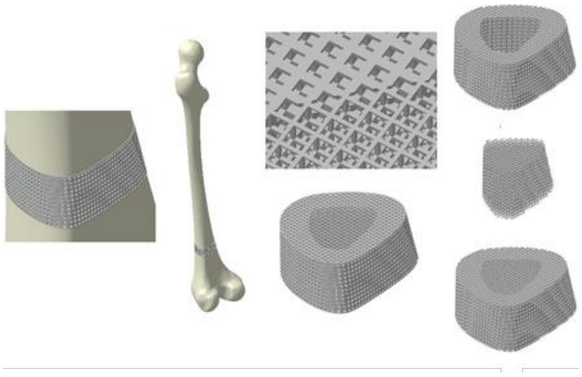

Fig. 2. Stages of scaffolding design

part of the scaffold. The unit cells of the outer part of the scaffold also had an incomplete structure, which was also corrected and the final structure of the scaffold was designed. Finally, the designed scaffold was assembled in the damaged part of the femur (Fig. 2).

4- Conclusions

The scaffold designed in this research has a geometry matching the geometry of the damaged part in its ideal state. It provides well the conditions required for cell proliferation and food release. Also, due to the design of the internal structure using two types of single cells, the designed scaffold has mechanical properties in accordance with the mechanical properties of damaged bone tissue. A scaffold was created for the reconstruction of the damaged part of the femur by repeating each unit cell in three dimensions. In order to check the mechanical properties, finite element analysis was performed.

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